ENVIRONMENTAL HEALTH PERSPECTIVES
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http://dx.doi.org/10.1289/EHP160

Received: 23 May 2015
Revised: 27 January 2016
Accepted: 4 May 2016
Published: 20 May 2016

Environ Health Perspect DOI: 10.1289/EHP160
Advance Publication: Not Copyedited

Reducing Emergency Department Visits for Acute Gastrointestinal Illnesses in North Carolina (USA) by Extending Community Water Service

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Running title: Reducing AGI by extending community water service

Acknowledgments: This research was supported by NIEHS T32ES007018 and by the Robert Wood Johnson Foundation under Mentored Research Scientist Development Award 70580. We are especially thankful to the following individuals and organizations for making available the data used in this analysis: Jenna Waggoner and John Wallace from NC DETECT; Julia Cavalier, Chandler Warner, and Eric Chai from the North Carolina (NC) Department of Environment and Natural Resources; Nirmalla Barros from the NC Division of Public Health (NCDPH); Aaron

Fleischauer from NCDPH and the US Centers for Disease Control and Prevention; and the NC State Laboratory of Public Health.

Disclaimer: NCDETECT is an advanced, statewide public health surveillance system. NCDETECT is funded with federal funds by NCDPH, Public Health Emergency Preparedness Grant, and managed though a collaboration between NCDPH and the UNC Department of Emergency Medicine's Carolina Center for Health Informatics. The NCDETECT Data Oversight Committee does not take responsibility for the scientific validity or accuracy of methodology, results, statistical analyses, or conclusions presented. The NCDETECT Data Oversight Committee includes representatives from the NCDPH, UNC NCDETECT Team and N.C. Hospital Association.

Competing financial interests: The authors have no competing financial interests related to this work.

ABSTRACT

Background: Previous analyses have suggested that unregulated private drinking water wells carry a higher risk of exposure to microbial contamination compared with regulated community water systems. In NC, approximately 35% of the state's population relies on private wells, but the health impact associated with widespread reliance on such unregulated drinking water sources is unknown.

Objectives: We estimated the total number of emergency department visits for acute gastrointestinal illness attributable to microbial contamination in private wells in North Carolina per year, the costs of those visits, and the potential health benefits of extending regulated water service to households currently relying on private wells for their drinking water.

Methods: We developed a population intervention model using 2007-2013 data from all 122 North Carolina emergency departments along with microbial contamination data for all 2,120 community water systems and for 16,138 private well water samples collected since 2008.

Results: An estimated 29,400 (95% CI 26,600 – 32,200) emergency department visits per year for acute gastrointestinal illness were attributable to microbial contamination in drinking water, constituting approximately 7.3% (95% CI 6.6-7.9%) of all AGI-related visits. Of these attributable cases, 99% (29,200; 95% CI 26,500-31,900) were associated with private well contamination. The estimated state-wide annual cost of emergency department visits attributable to microbiological contamination of drinking water is \$40.2 million (95% CI \$2.58-\$193 million), of which \$39.9 million (95% CI \$2.56-192 million) is estimated to arise from private well contamination. An estimated 2,920 (95% CI 2,650–3,190) annual emergency department visits could be prevented by extending community water service to 10% of the population currently relying on private wells.

Conclusions: This research provides new evidence that extending regulated community water service to populations currently relying on private wells may decrease the population burden of acute gastrointestinal illness.

INTRODUCTION

The introduction of the community water system (CWS) was one of the twentieth century's most significant public health advances (Cutler & Miller 2005). In the US, this intervention is credited with decreasing infant, child, and total mortality by 75%, 67%, and 50%, respectively, between 1900 and 1936 (Cutler & Miller 2005). However, despite the potential health benefits provided by CWSs and decades of investment in expanding drinking water infrastructure, 44.5 million US residents (14% of the population) lack access to a regulated community water supply and instead obtain drinking water from an unregulated source, typically a groundwater well but sometimes a spring or surface water source (Maupin et al. 2014). For regulatory purposes, a domestic water system (DWS) is defined as an individual household well or other residential water system with fewer than 15 connections or serving fewer than 25 people year round (U.S. Environmental Protection Agency 2015). Among US states, North Carolina (NC) has the second-largest population—3.3 million residents (35% of state residents)—relying on DWSs for their drinking water (Figure SM1, Supporting Material) (Maupin et al. 2014).

Private wells and other DWSs are not regulated by the US Safe Drinking Water Act and therefore are not subject to the same level of monitoring as CWSs. In order to improve the safety and quality of drinking water from DWSs, the NC General Assembly passed a law requiring all counties to institute a private drinking water well permit program by July 1, 2008 (General Assembly of North Carolina 2006). Under this program, all new private wells must be permitted and must undergo water quality testing at the time of construction. However, this program may not be as effective as desired, because routine monitoring is not required after the permit is granted, and wells constructed before 2008 are exempted. Furthermore, there are no requirements to treat private well water if contamination is detected.

The magnitude of waterborne disease attributable to contaminants in US private wells is thought to be substantial but is not well quantified. Previous US studies have sought to quantify microbial pathogen concentrations in private wells and in CWSs that use undisinfected groundwater (Allevi et al. 2013; Borchardt et al. 2003; Desimone and Hamilton 2009; Sandhu et al. 1979; Sworobuk et al. 1987), and a few studies have sought to establish relationships between self-reported health outcomes and microbial contaminant concentrations in drinking water (Heaney et al. 2013; Macler and Merkle 2000; Raina et al. 1999; Uhlmann et al. 2009; Wedgworth and Brown 2013; Borchardt et al. 2012). However, to our knowledge, no known US study has provided county-level estimates for an entire state of the burden of acute gastrointestinal illness (AGI) attributable to microbial contaminants in private wells. The limited knowledge of the magnitude of health risks associated with private well contamination suggests that a comprehensive burden of disease assessment could inform future decisions about whether to extend community water service to unserved/underserved areas or to establish other policies to protect the health of those relying on private wells.

To help fill the information gap on waterborne disease risks associated with US private wells and the potential health benefits of interventions to reduce risks, this paper develops a population intervention model (PIM) to quantify AGI risks attributable to microbial contaminants in NC private wells. We focus on AGI, because analyses of US waterborne disease outbreak data over the past four decades indicate that AGI was the health outcome of concern in 87.8% of outbreaks (Craun et al. 2010). The PIM method enables not only estimation of current risks but also potential risk reductions achievable if CWSs were extended to those relying on domestic wells. As described by Hubbard and Van Der Laan, PIM models are intended to estimate “the difference between a treatment-specific counterfactual population distribution and the actual population distribution of an outcome in the target population of interest" (Hubbard & Van Der Laan 2008). The PIM approach has been used to estimate the health effects of a range of interventions, from reductions in perceived stress to smoking cessation (Ahern, Hubbard, & Galea 2009; Fleischer, Fernald, & Hubbard 2010). A recent review recommended its use for quantifying the global disease burden associated with poor drinking water quality and lack of sanitation facilities (Clasen et al. 2014). However, this approach has not been used previously to estimate public health risks from contaminated private wells in the United States.

The majority of previous studies of microbial hazards of US private wells quantified microbial contaminant concentrations but did not extend their analyses to estimate the associated health risks. A recent US Geological Survey study of approximately 400 private wells throughout the US found that 34% were contaminated with total coliform bacteria and 8% were contaminated with *E. coli*. (Desimone and Hamilton 2009). A prior study in a central NC neighborhood found that 5 of 12 wells tested positive for fecal indicator bacteria but none of the 8 houses connected to a CWS tested positive (Heaney et al. 2013). A study of microbial contaminants in Virginia domestic wells found that 41% of 538 samples tested positive for total coliforms and 10% tested positive for *E. coli* (Allevi et al. 2013). A Wisconsin study found that 28% of 50 private wells tested positive for total coliforms and 8% for enteric viruses (Borchardt et al. 2003). In Preston County, West Virginia, a study of 155 private wells found that 68% were positive for total coliform bacteria (Sworobuke et al. 1987). Finally, a study of three rural South Carolina counties randomly sampled 460 private wells (representing approximately 10% of well users) and found that 85% of samples were positive for total coliforms (Sandhu et al. 1979). These studies suggest that the detection frequency of microbial contaminants is substantially higher in private wells than is currently permitted in CWSs under Safe Drinking Water Act regulations (which require that no more than 5% and 0% of samples test positive for total coliform and *E. coli* bacteria, respectively, each month).

Very few recent North American studies have sought to link AGI risks to microbial contamination of private drinking water wells (Raina et al. 1999; Uhlmann et al. 2009). A recent cross-sectional case study in Alabama found that drinking water that tested positive for fecal coliforms increased the odds of contracting AGI by a factor of 4.0 (95% CI 1.3 -14), regardless of whether the water was from a domestic well or a CWS (Wedgworth and Brown 2013). This study also found that 20% of samples from DWSs tested positive for fecal coliforms, a proportion that was 2.5 times higher than samples from households connected to a CWS. In addition, a recent study in British Columbia, Canada, estimated that individuals drinking water from private wells had a five-fold increase in AGI risk compared to those supplied with water from CWSs (Uhlmann et al. 2009). These past findings suggest that households relying on private wells are exposed to more waterborne pathogens than those served by CWSs and thus may suffer more negative health outcomes compared to municipally supplied households.

The study reported here applies a PIM approach in order to estimate the risk and cost of AGI associated with exposure to microbial contaminants in NC private wells. This is the first study to provide such a quantitative, comparative analysis for an entire state at the county level using local health outcome and water quality data to produce population-specific estimates. Application of the PIM method to assess NC waterborne disease risks is made possible by the establishment of two NC databases: one that tracks illnesses reported in every NC emergency department and another that houses all private well water quality sampling data collected through NC's DWS permitting program. Both databases are the result of laws enacted by the NC General

Assembly: a 2004 statute requiring the NC State Health Director to establish the NC Hospital Emergency Surveillance System and obligating all emergency departments to submit electronic records of all visits to the system on a daily basis (General Assembly of North Carolina 2004) and a 2006 law requiring a water quality test at the time of installation for all wells constructed on or after July 1, 2008 (General Assembly of North Carolina 2006). Our results not only identify NC counties that may benefit the most from expanding CWSs but also provide insights into the potential magnitude of the disease burden attributable to microbially contaminated, unregulated private wells in the United States. The method we demonstrate could encourage other states to develop databases similar to those in NC, in order to assess the burden of disease associated with lack of access to regulated drinking water systems.

METHODS

The PIM approach for estimating the burden of disease attributable to a particular risk factor relies on a causal inference framework that describes the relationship between the current population distribution of exposure to the risk factor and the incidence rate of the health outcome of interest for population groups exposed at different levels (Hubbard and Van Der Laan 2008). For this analysis, the exposure of interest is microbial contamination of drinking water from CWSs and DWSs, and the health outcome of interest is AGI. The following section describes the data sources used to characterize exposure to microbial contaminants in drinking water and the incidence rate of AGI in NC counties. Next, we describe the mathematics of the PIM approach, followed by the sources of data used to translate the PIM results into estimates of the health costs of AGI attributable to drinking water contamination.

Data

Private Well Water Quality Data

We received monitoring data for all newly constructed private wells for the 60-month period January 1, 2009–December 31, 2013, from the NC State Laboratory of Public Health (Barros April 1, 2014). The data set included results from tests of 16,138 private wells for total coliforms and *E. coli* (reported as presence-absence) and the county in which the well is located. According to to the 2006 new well construction law, "water samples shall be collected from the sample tap at the well or the closest accessible collection point to the water source with a tap capable of being disinfected, provided the sampling point shall precede any water treatment devices" (General Assembly of North Carolina 2006). Therefore, the well sample data do not account for in-home water treatment.

Data were received for 91 of the 100 NC counties. Among these 91 counties, observations were available for each of the 60 months in 70 counties. In the remaining 21 counties, the number of months for which observations were available ranged from 10 to 58. Due to the incomplete temporal coverage of these data, private well water quality in each county was represented as the proportion of all samples collected in the county during the 60-month time period that tested positive for total coliform bacteria. The statistical PIM model described below was fitted to data from the 91 counties for which well water quality data were available, but estimates of health impacts of private well contamination were estimated for all 100 counties on the basis of this statistical model. For the nine counties that did not report, in estimating health impacts we assumed the prevalence of microbial contaminants equaled the mean prevalence among bordering NC counties. We also conducted a sensitivity analysis in which exposure in these counties was instead assumed to equal the 15th and 85th percentiles of contamination prevalence in the state as a whole (25.6% and 51.0%, respectively), rather than the mean exposure in surrounding counties.

Community System Water Quality Data

The NC Department of Environment and Natural Resources (NCDENR) provided microbial water quality violation data for all 2,120 active NC CWSs from January 1, 2007–December 31, 2013 (Cavalier March 21, 2014). The data set contained information on monthly violations, which were defined as events wherein greater than 5% of samples over a 30-day period tested positive for total coliform bacteria, and acute violations, defined as the presence of *E. coli* in one or more follow-up analyses of samples testing positive for total coliform bacteria (US EPA 1989).

Population Served by Water System Type

The population served by CWSs and by private wells was determined using annual county population estimates from the US Census together with CWS data reported by NCDENR (Cavalier March 21, 2014). We calculated the county-specific population served by CWSs by summing all individual CWS populations within a given county. We assumed those not served by a CWS relied on private wells.

Emergency Department Visits for AGI

Since most AGI cases are unreported (Roy, Scallan, and Beach 2006), we used data on emergency department (ED) visits for AGI as a proxy for total AGI incidence. Data on the total number of reported ED visits for AGI between January 1, 2007, and October 31, 2013, were extracted from the NC Disease Event Tracking and Epidemiologic Collection Tool (NCDETECT), which includes records from all 122 EDs in NC (Fleischauer March 3, 2014). Due to potential privacy concerns, all patient identification data other than county of residence were removed, and data were aggregated by month. In keeping with prior research on AGI, records from NCDETECT containing the following International Classification of Diseases, Ninth Revision (ICD-9), diagnostic codes were retrieved: infectious GI illness (001–009); non-infectious GI illness (558.9); and diarrhea, nausea and vomiting (787.01–787.03, 787.91) (Colford et al. 2006; Messner et al. 2006; Roy et al. 2006; Tinker et al. 2009). In total, the database contained 2,769,620 ED visits that matched these criteria.

Population Intervention Model (PIM)

The PIM approach, which is based on modern causal inference theory, was used to estimate monthly AGI ED visits per county attributable to microbially contaminated CWSs and private wells under different exposure scenarios (Hubbard and Van der Laan 2008). To implement the PIM, a panel structure log-Poisson regression model with a log-person-month offset and temporally autocorrelated errors was fitted to monthly county-level health outcome and water quality data. The model form is as follows:

$$\ln(\mathrm{Y}_{i,j}/N_{i,j}) = \alpha + \beta_1\, C_{\mathrm{CWS}_{i,j}} + \beta_2\, E_{\mathrm{CWS}_{i,j}} + \beta_3\, C_{\mathrm{DWS}_i} + \beta_4\, Pov_i + \beta_5\, ED_i + +\beta_6\, I_i + \left(\textstyle\sum_{l=7}^{9} \beta_l\, \mathrm{R}_l\right) + \left(\textstyle\sum_{m=10}^{21} \beta_m\, \mathrm{t}_m\right) + \mu_j \qquad (1)$$

where $Y_{i,j}$ is the number of observed AGI ED visits by residents of county i during month j, $C_{CWS,i,j}$ is the proportion of the county population in county i exposed to a monthly Safe Drinking Water Act maximum contaminant level (MCL) violation during month j (determined by assuming all customers of a CWSs with a monthly MCL violation were exposed), $E_{CWSi,j}$ is the proportion of the county population exposed to an acute MCL violation, C_{DWSi} is the population proportion in county i potentially exposed to total coliform bacteria via a private well (determined by multiplying the fraction of wells testing positive by the county population proportion relying on private wells), $R_{i,l}$ indicates the region of the state where the county is located (Coastal Plain, Piedmont, or Mountain), t_m is an indicator variable for month of the year, $N_{i,j}$ is the county population, Pov_i is the proportion of the county population living in poverty, ED_i is an indicator variable representing whether county i contains an ED, and I_i is a binary variable representing the county proportion uninsured (=1 for counties exceeding the statewide mean of 16%). The first-order autoregressive error term is represented as u_j, where

$$\mu_j = \phi \mu_{j-1} + \epsilon_j \tag{2}$$

and the ϵ_j are assumed to be independent with a mean of zero. Annual county population estimates were obtained from the NC Office of State Budget and Management (NC Office of State Budget and Management 2015). Poverty and health insurance coverage data were obtained from the 2010 US Census (Minnesota Population Center, 2014). Region was used as an indicator variable to reflect distinct differences in landform and geology that may affect water quality, as indicated in previous studies (Markewich, Pavich, & Buell 1990). The model was fitted to data for the time period January 1, 2007—October 31, 2013, in order to maximize use of the ED visit data. Regression models were fit using STATA IC 12 (College Station, TX).

The fully parameterized, fitted regression model (equation 1) was used to estimate the observed AGI cases in each county attributable to microbial contamination of CWSs and pivate wells. The expected number of AGI cases for each county was estimated both under current exposure conditions and under multiple counterfactual scenarios in which different proportions of the population relying on private wells were provided with a connection to the nearest CWS. Risks under actual conditions were computed by using all parameters in the regression model to estimate $Y_{i,j}$ (the mean estimated number of AGI ED visits in county i during month j) under the current exposure scenario. Risks under counterfactual scenarios were computed in the same manner under multiple different scenarios: (a) zero exposure to contaminants in drinking water (either in CWSs or private wells); (b) zero exposure to contaminants in CWSs; (c) zero exposure to contaminants in private wells; (d) connection of 10% of the population currently relying on private wells to the nearest CWS. $Y_{i,j\text{-}counterfactual}$ for each county and month was estimated under each counterfactual exposure scenario by changing the relevant independent variables in equation 1 (e.g., for scenario b, $C_{CWSi,j}$=0) to predict the number of AGI cases under that scenario for each county and each month. The log change in AGI ED visits given the changes in exposure under each counterfactual scenario was then computed by subtracting the estimated log of the counterfactual case rate from the mean regression model estimate of current log of the case rate:

$$\Delta \ln(\frac{Y_{i,j}}{N_{i,j}}) = \ln(Y_{i,j}/N_{i,j}) - \ln(Y_{i,j-counterfactual}/N_{i,j}) = \beta_1 \left(C_{CWS_{i,j}} - C_{CWS_{i,j-counterfactual}}\right) + \beta_2 \left(E_{CWS_{i,j}} - E_{CWS_{i,j-counterfactual}}\right) + \beta_3 \left(C_{DWS_{i,j}} - C_{DWS_{i,j-counterfactual}}\right) \quad (3)$$

For each county, we summed the estimates of prevented cases across months for each data year, in order to develop annual estimates of avoided cases by county. We then averaged these annual estimates across the seven years for which ED data were available (correcting for the fact that only 10 months of data were available for 2013).

ED Visit Costs

In order to estimate the potential costs associated with ED visits for AGI, we employed cost data from the Medical Expenditure Panel Survey (MEPS), the largest source of healthcare expenditure data available in the United States (Agency for Healthcare Research and Quality 2015). MEPS data are collected annually from a large-scale survey of US households conducted by the Agency for Healthcare Research and Quality of the U.S. Department of Health and Human Services. According to MEPS, the mean and median costs of an ED visit in the southern United States in 2012 (the most recent year for which compiled data are available) were $1,366 and $740, respectively (Agency for Healthcare Research and Quality 2012). To represent the potential cost range, we therefore modeled ED visit costs as lognormally distributed with geometric mean $740 and geometric standard deviation $3.03.

RESULTS

Microbial Contaminants in NC Drinking Water

Summary statistics for the compiled CWS and private well data show that microbial contaminants are much more common in private wells than in CWSs. Among private wells, 35.7% of the 16,138 samples collected during 2009-2013 tested positive for total coliforms, and 1.37% tested positive for *E. coli*. In comparison, 0.421% of 497,203 CWS samples collected during 2007-2013 tested positive for total coliforms and 0.0881% of 72,631 samples were positive for *E. coli*. On average 1.48% of the population in any given county was exposed to total coliform bacteria via a CWS in any given month, while 11.7% of the county population was exposed via a private well (Table 1), even though CWS customers outnumber private well users in most counties (Figure SM1). Exposures varied widely across the state (Figures SM2-3). Population proportions exposed to contaminants in private wells tended to be higher in the western, mountain region (Figure SM2) due to the greater reliance on private wells, while exposure to CWS contaminants was more common in the Coastal Plain (Figure SM3).

ED Visits for AGI

An average of 405,000 (SD=38,500) AGI ED visits per year were reported in NC between 2007 and 2013. The overall rate of AGI ED visits from all causes varied substantially across the state and with time (Figure SM4 and Table 1). The average number of monthly visits across all the county-months of available data was 3.61 per 1,000 people (equivalent to 43.3 visits per 1,000 people per year) but ranged from 0.164 to 13.5 per 1,000 people per month (1.96 to 162 visits per 1,000 people per year) (Table 1). Across counties, the number of visits averaged over all months ranged from a low of 1.17 per 1,000 people per month (14 visits per 1,000 people per year) to a high of 8.83 (106 visits per 1,000 people per year) (Figure SM4).

Associations between ED Visits for AGI and Regression Model Covariates

The longitudinal multivariate regression model (equation 1) showed that ED visits for AGI in NC counties were significantly associated with water quality characteristics (Table 2 and Figure 1). ED visits for AGI increased with the prevalence of total coliform bacteria in private wells along with the fraction of the county population exposed to microbial contaminants in community water systems in any given month.

The regression model results also highlight other important influences on rates of ED visits for AGI. Poverty has an important influence. The beta-coefficient on poverty (2.57) implies that an average of 0.25 additional ED visits for AGI per 1,000 people per month occur in counties at the highest quartile of state-wide poverty (19.9% living in poverty) than in counties at the lowest quartile (13.5%) after adjusting for measures of drinking water quality. In addition, as suggested in Figure SM4 and demonstrated by the regression coefficients in Table 2, AGI ED visit rates are significantly higher in the Coastal Plain region than in the other two regions and are lowest in the Mountain Region. Visit rates are lower in counties where more people are uninsured and higher in counties with EDs, as demonstrated by the negative and positive signs on the regression coefficients for these variables. Seasonally, AGI visit rates are highest in winter (December through February), demonstrated by the negative coefficients on non-winter months.

ED Visits Attributable to Domestic Well Contamination

Employing this regression model in the PIM analysis suggests that an estimated 29,400 (95% CI 26,600 – 32,200) ED visits for AGI were attributable to microbial contamination in drinking water each year, constituting approximately 7.3% (95% CI 6.6–7.9%) of all ED visits for AGI (Table 3, top row). Approximately 99% of the attributable visits (29,200, 95% CI 26,500 – 31,900) were associated with private well contamination, and the remaining 1% were associated with CWS contamination (Table 3, top row). The PIM approach estimates that if 10% of the population relying on private wells in each county were connected to a local CWSs, then 2,920 (95% CI 2,650-3,190) ED visits for AGI could be prevented across NC each year (Table 3, top row).

The health burden associated with microbial contamination of domestic wells varies substantially by county. The proportion of AGI ED visits potentially attributable to DWSs ranges by county from 0.525% to 27.1% (Figure 2). County-level rates of attributable AGI visits per 1,000 people per year range from 0.179 to 17.7 (Figure 3).

Costs of ED Visits Attributable to to Domestic Well Contamination

The estimated state-wide cost of ED visits for AGI attributable to microbial contamination in drinking water is $40.2 million (95% CI $2.58-$193 million). Of this total,

$39.9 million (95% CI $2.56-192 million) is estimated to arise from private well contamination (Table 3). Extending community water service to 10% of the population in each county currently relying on private wells would decrease annual AGI ED visit costs by $3.99 million (95% CI $256,000-$19.2 million). The total net present value of this potential benefit over 30 years, assuming a 3% discount rate (the approximate current interest rate for municipal bonds), is $78.1 million (95% CI $5.01 million – $376 million).

Sensitivity Analysis

Since data on the prevalence of microbial contaminants in private wells were unavailable for 9 of NC's 100 counties, we analyzed the sensitivity of the estimated disease burden associated with private well contamination to alternative assumptions about well water quality in these nine counties. Our best estimate (Table 3, top row) assumes that the prevalence of private well contamination in each of these counties equals the mean of the prevalences in the surrounding counties. Alternative estimates 1 and 2 (Table 3, bottom rows) assume that the prevalences of private well contamination in each of these nine counties are equal to the 15th and 85th percentile values of prevalences in the state as a whole. Overall, these changes had a small effect on our results, changing the baseline estimates by about ±6% (Table 3).

DISCUSSION

We estimated that approximately 7.3% (95% CI 6.6-7.9%) of all ED visits for AGI from 2007 to 2013 were potentially attributable to microbial contamination of NC drinking water. About 99% of the attributable cases were associated with contamination in private wells, according to our estimates. On average, ED visits potentially attributable to private well contamination are estimated to cost $39.9 million per year.

To our knowledge, there have not been any previous assessments of AGI risk due to private wells in the US; the closest equivalent studies on drinking water quality we could find in the literature were two studies of non-disinfected groundwater. Using a quantitative microbial risk assessment approach, Macler and Merkle (2000) estimated that microbial contamination of non-disinfected community groundwater systems contributed 0.75–5.0 million AGI cases annually in the US (5-32% of all cases among the population using non-disinfected community groundwater systems). Borchardt et al. (2012) found that 6–22% of self-reported AGI cases were attributable to viruses in tap water in 13 Wisconsin communities that did not disinfect their community groundwater supplies. Our estimate that 7.3% of AGI cases seen in North Carolina EDs are attributable to contaminated private wells is on the lower end of estimates reported in studies of non-disinfected groundwater CWS studies.

These results lend support to the value of total coliform bacteria as indicators of public health risk for private wells. Our results show that for a county in which 35% of theh population relies on private wells (the state-wide average), every 10% increase in the prevalence of total coliform bacteria in private wells increases the county-wide number of ED visits for AGI by 3.0%, controlling for demographic factors. Although researchers have long sought improved indicators of pathogens in drinking water (e.g., Savichtcheva and Okabe 2006), these results suggest that continued monitoring of private wells for total coliform bacteria can provide valuable information on public health risks of private well contamination. This finding supports results from a recent review of 20 years of research on pathogens in water by Payment and Locas (Payment and Locas 2011). Specifically, Payment and Locas found, “Quite interestingly, in our studies of groundwater . . . , it was the nonfecal indicators, total coliforms, and aerobic endospores that were found most frequently in virus-positive samples.” Payment and Locas reported that *E. coli* and *Enteroocci*, which are more specific indicators of fecal contamination than total coliforms, were absent in 20% and 30% of groundwater samples testing positive for culturable human enteric viruses, respectively, while total coliform bacteria were positive in all virus-positive samples. Payment and Locas concluded,

> The presence of total coliforms in groundwater indicates that microorganisms from surface water have been able to reach the aquifer and a more rigorous monitoring should begin for other microorganisms (pathogenic) which might also reach the aquifer. When fecal indicators are detected, anything can happen, and will happen, with potential serious public health implications.

While most NC communities lacking regulated water service are located in rural areas, especially in the mountainous western part of the state (Figure SM1), some are located in relatively population-dense neighborhoods on the fringes of, or entirely surrounded by, cities and towns served by CWSs (Naman and MacDonald Gibson 2015; MacDonald Gibson et al. 2014). In some cases, these communities were historically denied access to municipal services during the era of legally sanctioned racial segregation and still have not received access to services (Gilbert 2013; Johnson, Parnell, Joyner, Christman, & Marsh 2004; Marsh, Parnell, & Joyner 2013). A handful of community-level case studies documenting such disparities exist (Johnson et al. 2004; MacDonald Gibson, DeFelice, Sebastian, & Leker 2014; UNC Center for Civil Rights 2006). One example is a neighborhood adjacent to Mebane, a town of about 8,000 located 50 miles northwest of Raleigh. Recently, as a result of more than a decade of action by a local community organization, Mebane extended CWS services to 90 homes, but more than 400 homes remain without service (Heaney et al. 2011; Wilson 2011). Such population-dense areas near existing infrastructure may be the most appropriate targets for future CWS expansion due to the likely relatively lower cost (compared to rural areas) of extending existing water distribution networks.

Local governments and utility providers traditionally make decisions pertaining to water service, and a large portion of these decisions are made on a cost-benefit basis. Constructing water mains is expensive, and it is not feasible to provide regulated water statewide. However, identifying areas of greater population density that may be in close proximity to existing infrastructure along with factoring in the potential health benefits may make expansion economically feasible. Future research should identify such communities.

LIMITATIONS

A number of limitations are inherent in the data analyzed in this research. First, due to a lack of pathogen monitoring, we relied on the presence of total coliform bacteria as the indicator of potential exposure to microbial pathogens, because these data are routinely collected by CWSs and when new private wells are constructed. Such microbial indicators are used for reasons of practicality and cost since large water samples are required to detect pathogens and sampling techniques are costly (e.g. *Giardia* and viruses) (Hancock et al. 1998; Macler and Regli 1993; Regli et al. 1991). The presence of a microbial indicator does not confirm but rather increases the probability of pathogen presence; likewise, the absence of indicator organisms does not guarantee the water is pathogen free (Payment and Locas 2011). Therefore, our understanding of the presence of pathogens is conditional on the indicator organism, so we may have over- or under-estimated exposure (Borchardt et al. 2012; Johnson et al. 2011; Kay et al. 2007; Payment and Locas 2011). Potentially amplifying this effect is that the private well water quality samples were collected prior to the location of in-home treatment systems, where such systems were in use. In contrast, community water systems collect water samples after treatment. In-home devices can increase, decrease, or have no effect on levels of microbial contamination. For example, Chaidez and Gerba found that in-home activated carbon filters “may amplify the numbers of bacteria present in the tapwater by promoting biofilm formation" (Chaidez and Gerba 2004). While reverse-osmosis, distillation, and disinfection systems can remove microbial contaminants, previous studies suggest that the prevalence of use of such devices is relatively low among private well owners. For example, a survey of 221 private well owners in Michigan found that 8.6% used a home treatment device capable of removing microbial contaminants (Slotnick, Meliker, and Nriagu, 2006).

A second limitation is the assumed uniform exposure across the population served by each CWS for a given month with a violation and the similar uniform exposure assumed for private wells within a county within the time period analyzed. These assumptions could result in under- or over-estimates of the number of people exposed if the proportion of private well users exposed to microbial indicator organisms in a given county was not constant over the course of the analysis time period or if the CWSs population was not uniformly exposed during a given month. Exposure may be over-estimated if some residents exclusively drink bottled water. Also, all new well owners receive public health recommendations to disinfect their wells and/or install treatment systems if the well tests positive for contamination and as a result may take corrective action, which would reduce exposure levels; such corrective actions are not reflected in this analysis. On the other hand, underestimates of exposure could have occurred if private well water quality deteriorated after construction. Our private well data set included only newly constructed wells, which may not be representative of older private wells with aging components. Similarly, we could have underestimated exposure to CWS contamination, since exposure for CWSs was defined as an MCL violation (more than 5% of samples tested positive in a given month), while in fact exposure may still occur when fewer than 5% of samples test positive.

A third limitation arises from the geopolitical level of the analysis. The finest resolution of NCDETECT's data on AGI ED visits made available for this research was at the county level. Therefore, we assumed a homogeneous distribution of AGI across each county and, as a result, may have introduced bias in our estimates. In addition, as a result of the county-level aggregation of the health outcome data, exposure estimates also needed to be expressed at the county level. Exposure due to a given water system type (private well or CWS) at the county level was estimated using a population weighting approach. CWSs thus contributed to the risk estimates proportional to their population size, while private wells were assumed to have a uniform size across all systems in the county. Further, the aggregation of CWS exposure to the county level has the potential to be biased due to the influence of larger systems. These assumptions were unavoidable given the nature of reported data on microbial indicator organisms.

A fourth limitation arises from the way in which ED visit data are coded. Patient data are classified based on ICD-9 codes, which are used for billing rather than diagnosis and thus may contribute to under- or over-estimation of the true health risk. Under estimation may occur when two or more conditions are present during a visit, and medical personnel elect to report the more severe or more important billing code, neglecting to mention the AGI that was in fact present. Over estimation may occur due to general coding protocols of an ED and the assumption of which comorbidities are present for a given condition.

A final caveat is that because our study involved neither random sampling nor random allocation, results may be due to the factors under investigation, unmeasured factors, or measurement error, but not chance (Greenland 1990). Due to this, along with the large sample size, caution should be taken in interpreting the statistical significance of the PIM model.

Overall, the estimates presented here likely underestimate the total health burden resulting from microbial contamination of domestic wells. The health outcome dataset captures only a fraction of all AGI cases. A previous study based on phone surveys of 52,840 people across the United States estimated that 6.4% (95% CI 5.0-7.8%) of persons with AGI visit the ED (Jones et al. 2007). Thus, every ED visit potentially represents approximately 16 (=1/0.064) AGI cases.

CONCLUSIONS

Despite the limitations, this analysis demonstrates a new method for estimating waterborne disease risks associated with lack of community water service that could be applied not only in the United States and other developed nations but also in developing countries as was recently recommended by Clasen et al. (Clasen et al. 2014). In the United States, concerns about disparities in water service levels have been reported recently in communities ranging from Alaska Native villages to agricultural areas in central California to the Southeast (Balazs and Ray, 2014). The method demonstrated in this paper could be used to quantify the public health implications of these disparities.

Historically, public health practitioners have played a critical role in persuading municipalities to adopt water treatment systems. Our finding that some 29,200 annual ED visits for AGI costing approximately $39.9 million are potentially attributable to contamination of private wells demonstrates that expanding regulated water services has the potential for substantial health benefits. Where service extensions are not technically or economically feasible, county or state governments could expand services to support private well owners in maintaining the integrity of their wells, routinely testing their water quality, and, where necessary, in providing and maintaining in-home treatment. Public health practitioners could use the information in this analysis to encourage a new dialogue with local water utilities and governments about options for extending municipal water service into un-served areas and for providing other support measures where such extensions are not feasible.

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Table 1. Summary statistics for the key variables included in the regression model (n=8,200 county-months)

Variable	Mean (SD)	Minimum	First Quartile	Median	Third Quartile	Maximum
County population ($N_{i,j}$)	95,355 (141,743)	4,407	24,628	55,622	106,913	919,628
Reported emergency department visits for acute gastrointestinal illness per 1,000 people per month	3.61 (1.84)	0.164	2.25	3.28	4.64	13.5
Percent of county population exposed to total coliform bacteria via private wells (C_{DWSi})	11.7 (7.78)	0.622	5.02	10.8	16.5	32.1
Percent of county population exposed to a monthly violation of regulations on total coliform bacteria in community water systems ($C_{CWSi,j}$)	1.48 (8.66)	0.00	0.00	0.00	0.00	95.8
Percent of county population exposed to an acute violation of regulations on *E. coli* bacteria in community water systems ($E_{CWSi,j}$)	0.0884 (2.23)	0.00	0.00	0.00	0.00	95.5
Percept of population living in poverty (Pov_i)	16.7 (4.52)	8.01	13.5	16.1	19.90	29.0
Has an emergency department (ED_i)						
Yes	83	NA	NA	NA	NA	NA
No	17	NA	NA	NA	NA	NA
>16% of residents uninsured (binary) (I_i)						
Yes	83	NA	NA	NA	NA	NA
No	17	NA	NA	NA	NA	NA
Region						
Coastal Plain	41	NA	NA	NA	NA	NA
Piedmont	42	NA	NA	NA	NA	NA
Mountain	17	NA	NA	NA	NA	NA

Table 2. Beta coefficients from log-Poisson regression model fitted to monthly county-level emergency department and water quality data

Variable	Beta	(95% CI)
Fraction of county population exposed to total coliform bacteria via private wells (C_{DWSi})	0.844	(0.767, 0.921)
Fraction of county population exposed to a monthly violation of regulations on total coliform bacteria in community water systems ($C_{CWSi,j}$)	0.00737	(0.00390, 0.0108)
Fraction of county population exposed to an acute violation of regulations on *E. coli* bacteria in community water systems ($E_{CWSi,j}$)	0.0599	(0.0520, 0.0678)
Fraction of the county population living in poverty (Pov_i)	2.57	(2.44, 2.70)
Presence of an emergency department (binary) (ED_i)	0.102	(0.0714, 0.132)
Greater than 16% of population uninsured (binary) (I_i)	-0.271	(-0.286, -0.255)
Region (R)		
Coastal Plain	Referent	-
Piedmont	-0.111	(-0.124, -0.0990)
Mountain	-0.495	(-0.519, -0.471)
Month (m)		
January	Referent	-
February	0.0285	(0.0267, 0.0303)
March	0.0996	(0.0972, 0.102)
April	-0.0811	(-0.0840, -0.0783)
May	-0.131	(-0.134, -0.127)
June	-0.188	(-0.192, -0.185)
July	-0.181	(-0.185, -0.178)
August	-0.173	(-0.177, -0.170)
September	-0.180	(-0.183, -0.176)
October	-0.164	(-0.167, -0.161)
November	-0.158	(-0.161, -0.155)
December	-0.0377	(-0.0397, -0.0357)
Constant (α)	-5.94	(-5.98, -5.90)

Table 3. Emergency department (ED) visits for acute gastrointestinal illness attributable to microbial contamination of drinking water in North Carolina and associated costs under alternative scenarios

Scenario	ED Visits Attributable to Drinking Water Contamination (#/Year)	ED Visits Attributable to Private Well Contamination (#/Year)	Cost of ED Visits Attributable to Private Well Contamination (Millions/Year)	ED Visits Preventable by Extending Water Service to 10% of Private Well Population (#/Year)	Value of ED Visits Preventable by Extending Water Service to 10% of Private Well Population (Millions/Year)
Best estimate	29,400 (26,600-32,200)	29,200 (26,500-31,900)	$39.9 ($2.56-$192)	2,920 (2,650-3,190)	$3.99 ($0.256-$19.2)
Alternative estimate 1	27,600 (25,000-30,200)	27,600 (25,0000-30,200)	$37.7 ($2.21-$180)	2,740 (2,480-2,990)	$3.77 ($0.221-$18.0)
Alternative estimate 2	31,300 (28,400-34,200)	31,300 (28,400-34,200)	$42.4 ($2.52-$198)	3,110 (2,820-3,390)	$4.23 ($0.251-$19.8)

NOTE: Alternative estimates 1 and 2 were derived by assuming the prevalences of total coliform bacteria in private wells in each of the 9 counties that did not provide private well data were equal to the 15th and 85th percentile values of the state-wide prevalence, respectively. The 9 counties for which data were missing were Buncombe, Caldwell, Catawba, Cherokee, Cleveland, Gaston, Haywood, New Hanover, and Wake.

Figure 1. Observed and predicted number of emergency department visits for acute gastrointestinal illness, illustrating fit of the log-Poisson regression model.

Figure 2. Estimated percentage of emergency department (ED) visits for acute gastrointestinal illness (AGI) attributable to private wells. (Map data courtesy U.S. Census Bureau.)

Figure 3. Estimated annual rate of emergency department (ED) visits per 1,000 people for acute gastrointestinal illness (AGI) attributable to private wells. (Map data courtesy U.S. Census Bureau.)

Environ Health Perspect DOI: 10.1289/EHP160
Advance Publication: Not Copyedited

Figure 1.

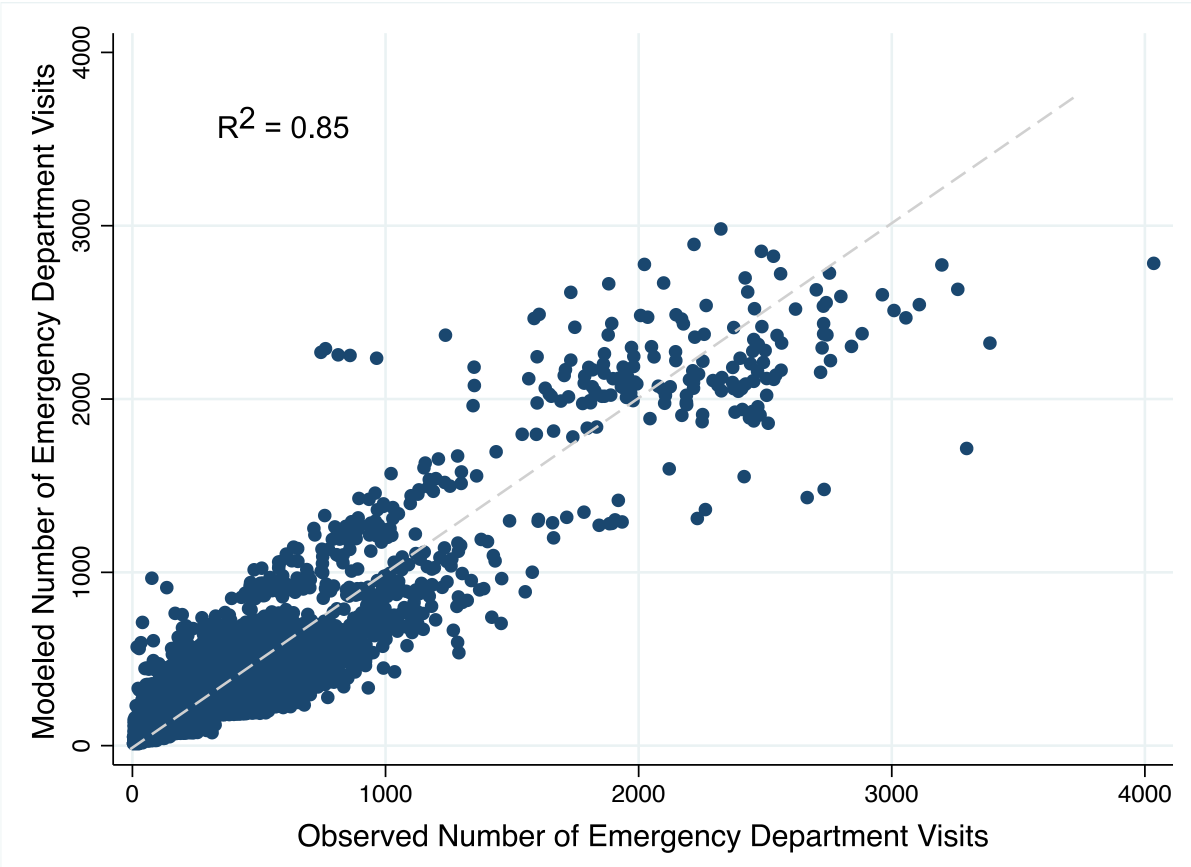
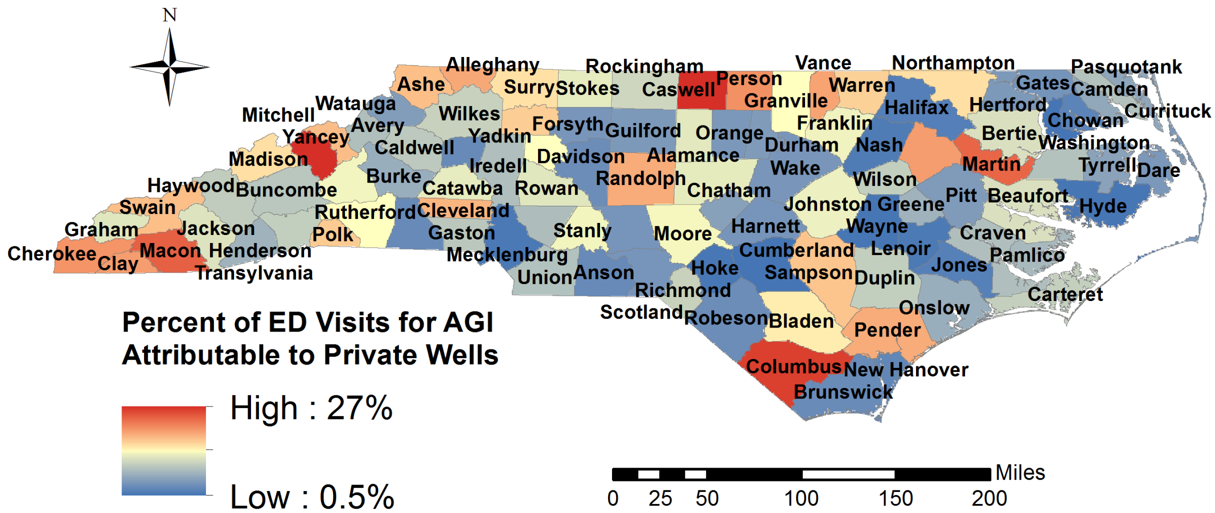


Figure 2.


N
Percent of ED Visits for AGI
Attributable to Private Wells
High : 27%
Low : 0.5%
Miles
0
25
50
100
150
200
Alleghany
Ashe
Rockingham
Surry
Stokes
Caswell
Person
Vance
Warren
Granville
Northampton
Pasquotank
Gates
Camden
Currituck
Hertford
Halifax
Chowan
Bertie
Washington
Tyrrell
Dare
Martin
Mitchell
Watauga
Wilkes
Yancey
Avery
Yadkin
Forsyth
Guilford
Orange
Durham
Franklin
Nash
Madison
Caldwell
Iredell
Davidson
Alamance
Wake
Wilson
Haywood
Buncombe
Burke
Catawba
Rowan
Randolph
Chatham
Johnston
Greene
Pitt
Beaufort
Hyde
Swain
Rutherford
Cleveland
Gaston
Stanly
Moore
Harnett
Wayne
Craven
Graham
Jackson
Polk
Cherokee
Clay
Macon
Henderson
Transylvania
Mecklenburg
Union
Anson
Richmond
Hoke
Cumberland
Lenoir
Jones
Pamlico
Sampson
Duplin
Carteret
Scotland
Robeson
Bladen
Onslow
Pender
Columbus
New Hanover
Brunswick

Environ Health Perspect DOI: 10.1289/EHP160
Advance Publication: Not Copyedited

Figure 3.